Large-scale integrated quantum photonic technologies for communications and computation

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Abstract: Quantum photonics has emerged as a promising approach to realizing large-scale and complex quantum technologies. Here we overview recent developments presenting circuits comprising hundreds of photonic components integrated into single coherent quantum systems.

OCIS codes: (130.0130) Integrated optics; (270.5565) Quantum communications; (270.5585) Quantum information and processing

1. Introduction

Photonics is a promising approach to realizing quantum information technologies, where entangled states of light are generated and manipulated to implement fundamentally new modes of computation, simulation and communication, as well as enhanced measurements and sensing. Historically bulk optical elements on large optical tables have been the means by which to realize proof-of-principle demonstrators in quantum physics. Integrated quantum photonics has enabled a step change in this technology by controlling and manipulating single photons within miniature waveguide circuits. This technology approach is now being used to pioneered breakthroughs in quantum communications, quantum sensing and quantum information processing. Here we present recent developments in chip-to-chip quantum communications and on-chip quantum information processing.

2. Chip-based quantum communications

Quantum Key Distribution (QKD) provides a provably secure approach to share secrete keys used to encrypt information by transmitting single photons through a quantum channel. It is one of the first commercially available quantum technologies and a leading candidate for securing communications against attacks from future quantum computers. Integrated photonics provides a stable, compact, miniaturized and robust platform to implement quantum communications systems. The inherent phase stability of integrated photonics makes it particularly suitable for manipulating quantum information encoded in different time-bins, an encoding extensively used in fiber-based QKD systems.

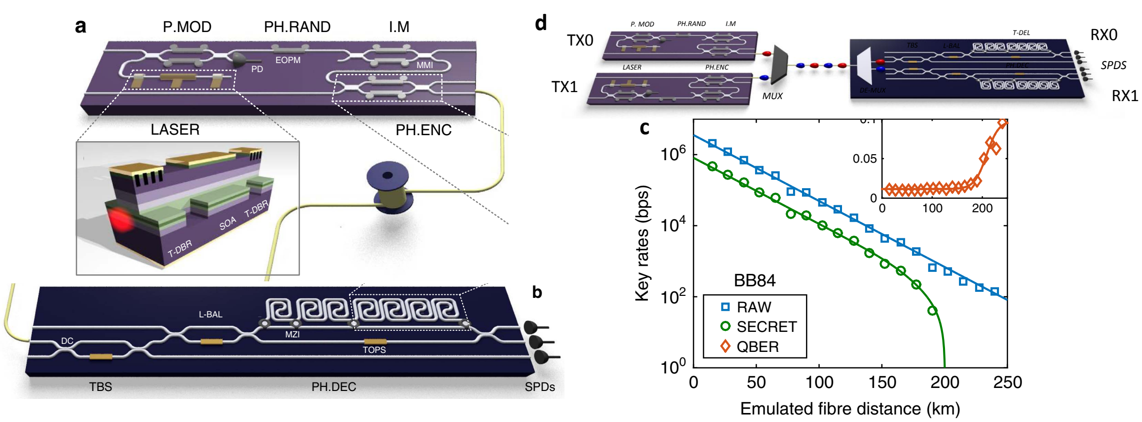

Figure 1: Chip-to-chip quantum communication system (a) InP transmitter chip (b) SiON receiver chip (c) Key rate for emulated fiber distance (d) WDM QKD link

Chip-based QKD transmitters have been implemented in both the InP[1] and Silicon [2, 3] material platforms, with the first demonstration of a fully integrated chip-to-chip QKD system implemented with an InP transmitter chip and a Silicon Oxynitride receiver chip (Figure 1a) [1]. These chips provide a complete chip-to-chip quantum photonic solution, and through programmable quantum circuitry could implement multiple QKD protocols, including: Coherent One Way (COW) operating at a 860MHz state rate; Differential Phase Shift (DPS) at a 1.76GHz state rate; and BB84 at a 560MHz state rate (see Figure 2 for an example). The data rate of these systems can be increased through wavelength division multiplexing (WDM), where multiple secrete keys are distributed within a single optical fiber on different wavelengths. Figure 1c show one such approach were a WDM-QKD system was implemented using two GHz clocked InP QKD transmitters and a single. Silicon Oxynitride receiver with integrated de-multiplexing. The InP chips are fully integrated, incorporating all the necessary components including a tunable laser source and high-speed phase modulators. Using on-chip asymmetric MZI filters for wavelength de-multiplexing, the receiver splits the two channels into independent copies of the reconfigurable decoding circuitry. The combined WDM channels increase the secrete key rate by a factor of two, to 1.11 Mbit/s over a 20 km emulated fiber. The increase in rates, and ability to scale up these circuits opens the way to new and advanced integrated quantum communication technologies and larger adoption of quantum-secured communications.

Implementing the transmitter in a silicon-based technology platform is appealing due to its relatively low cost, compatibility with CMOS electronics and suitability for very large-scale integration and manufacturing. However, silicon lacks a natural chi-2 non-linearity typically used for high performance modulation, and instead utilizes carrier injection or depletion modulators which suffer from high insertion loss, phase-dependent loss, and saturation - which presents a challenge for QKD state preparation. To overcome these problems a combination of slow but lossless thermal phases shifters with fast but lossy carrier-based modulators can be used to reduce the phase-dependent loss in these systems, to ensure fast encoding of all four states required for the BB84 protocol. This principle was demonstrated in two fully integrated silicon-based transmitter chips [3]: one designed for time-bin encoding (Figure 2a), and one for polarisation encoding (Figure 2b). These QKD transmitters, based on CMOS-compatible silicon photonics, provide a route to the mass-manufacture of quantum-secured communications devices, and ultimately the seamless integration with micro-electronics circuits.

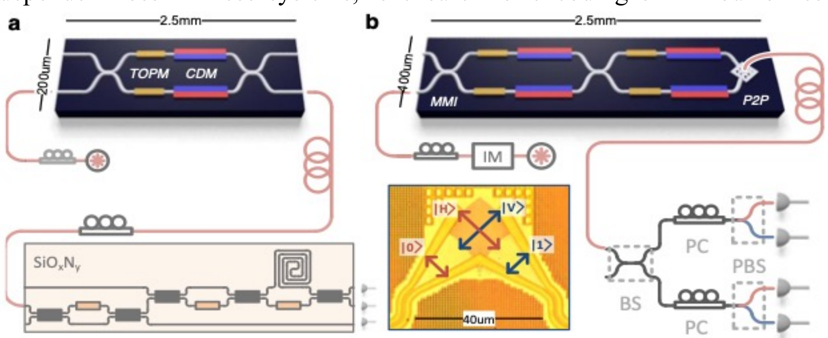

Figure 2: Silicon-based QKD transmitters (a) time-bin encoding (b) polarization encoding.

3. Chip-based quantum information processing

Quantum computing has generated much interest for its potential ability to outperform classical computing for many important tasks. Photons are considered as a promising candidate for implementing quantum computation owing to their properties of long coherence time, ease of manipulation and light-speed transmission. The silicon-based quantum technology platform, where quantum states of light can be generated and manipulated using entirely silicon-based waveguide circuits [4], offers a range of benefits for quantum information processing, including high nonlinearities for efficient on-chip generation of quantum states of light, and high component densities for complex circuits. Using this silicon quantum photonic technology platform a wide range of quantum information processing demonstrators have been realized. Here we focus specifically on the more recent large-scale implementations.

Programmable two-qubit photonic quantum processor

One such example of a complex quantum photonic circuit is presented in Figure 3, showing a fully reconfigurable silicon quantum photonic device able to implement universal two-qubit unitary quantum operations[5]. This approach adopts an optical linear-combination protocol that utilizes only two-photon-entanglement and extended spatial freedom of the photons. The device integrates 4 photon-sources, 4 laser pump rejection filters, 82 beam splitters and 58 programmable thermo-optic phase shifters (over 150 total photonic elements). The device has been programmed to implement 98 different two-qubit quantum logic gates (including CNOT, CZ, CH, SWAP, iSWAP and SWAP), and the device performance was evaluated by performing quantum process tomography for each operation, achieving an average quantum process fidelity of 93.2±4.5%. This universal two-qubit silicon photonic quantum processor is able to initialize, operate and analyze arbitrary two-qubit states and processes. It is fully programmable, robust and providing a universal platform for implementing quantum information processing applications.

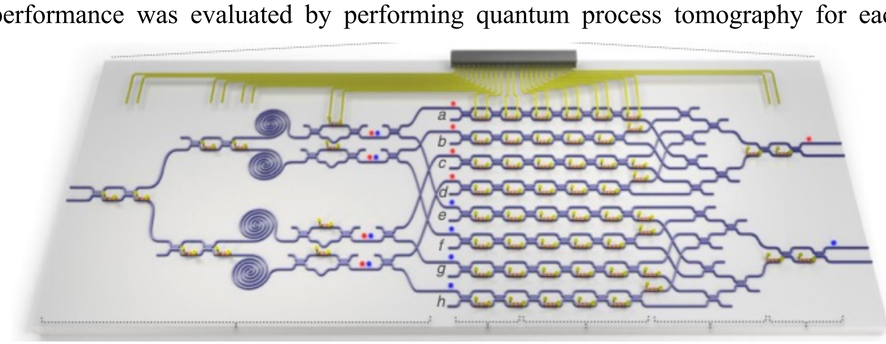

Figure 3: A programmable silicon quantum photonic circuit for universal two-qubit unitary quantum operations.

Large-scale multi-dimensional quantum photonics

Multi-dimensional quantum systems exhibit distinct quantum properties and offer improvements in key applications such as increasing capacity in quantum communication, strengthening quantum correlations, and enriching quantum simulation and computing schemes. Photons represent a promising platform able to naturally encode and process these 'qudits' in various degrees of freedom, e.g., orbital angular momentum, temporal bin and frequency. However, these approaches present limitations in terms of controllability, precision, universality and a full integration of elements, which represent bottlenecks for further developments of multidimensional quantum photonic technologies. By utilizing large-scale silicon quantum photonics, a chip was realized that could create, control and multidimensional entanglement up to dimensions 15 × 15 [6]. The chip (Figure 4) comprised 16 photon sources that use spontaneous four-wave mixing to generate photon pairs in a superposition across 16 optical modes; 93 thermo-optic phase shifters; 122 multimode interference beamsplitters; 256 waveguide crossers and 64 grating couplers. A total of 550 photonic components monolithically integrated on a single chip. This chip enables the generation of multidimensional entangled states with an arbitrary degree of entanglement and arbitrary multidimensional measurements with very high fidelity, verified by quantum state tomography and Bell violations.

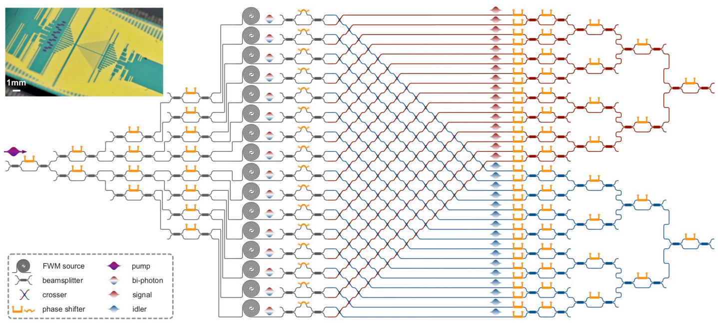

Figure 4: Highly reconfigurable quantum circuit for the generation, control and analysis of muti-dimensional quantum entanglement.

Programmable four-photon graph states on a silicon chip

Modern approaches to quantum information processing demands the generation of large entangled quantum states, typically graph states. To investigate such states of light, integrated quantum circuits are required that can generate and manipulate indistinguishable multi-photon states. Figure 5 show the first integrated quantum circuit capable of the on-chip generation and manipulation of four-qubit, four-photon graph states. The device generates two pairs of photons on-chip, then applies a switchable entangling gate (performing either a fusion or a controlled-*Z* operation) in order to entangle the qubit states and access all 6 of the 4-qubit graph states - creating genuine four-qubit entanglement. Whether the entangling gate is set to perform a fusion or a CZ operation determines the type of entanglement in the produced four-qubit state. The fusion operation yields Greenberger – Horne – Zeilinger – type entanglement, whereas the CZ operation yields entanglement of the cluster state type. These comprise the only two classes of graph-state entanglement in four qubits, which are locally equivalent to the entire set of four-qubit graph states. The device produces Bell pairs with state-of-the-art fidelity, and the star-type graph state (inset of Figure 5) are verified by measuring that state's stabilizers.

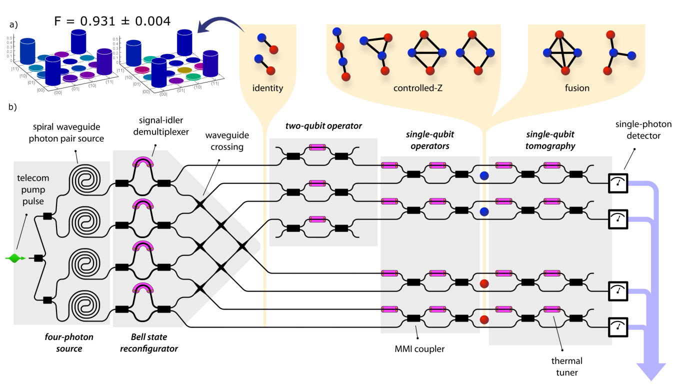

Figure 5: Graph state generator: (a) Reconstructed density matrices of on-chip Bell pairs, (b) Schematic of device

4. Conclusion

Integrated quantum photonics is a versatile technology platform that is proving invaluable in the development of future quantum information technology applications, particularly in quantum communications and quantum computation. Large-scale quantum photonic circuits enable the on-chip generation and precise manipulation of complex photon states of light, whilst these stable, compact, miniaturized and robust platforms are also delivering the next generation of quantum communications devices.

References

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